Sand Ripple Dynamics on the Inner Shelf

Donald N. Slinn
Department of Civil and Coastal Engineering, University of Florida
Gainesville, FL 32611-6590,
Phone: (352) 392-9537 x 1431 Fax: (352) 392-3466 E-mail: slinn@coastal.ufl.edu

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LONG-TERM GOALS

The goals of this work are to develop better understanding and predictive capability for the development and evolution of sand ripples in coastal oceans.

OBJECTIVES

We have developed two high resolution, three-dimensional, coupled hydrodynamic – sediment transport, live-bed models to simulate sand ripple growth and evolution. We are using these models to explain fundamental ripple dynamics. We aim to demonstrate the contributions from bed-load and suspended load to ripple growth and decay, and the importance of interactions between kinetic and potential energy in the sediment load. The three-dimensional models simulate the response of the sea-bed under oscillatory and wave-current induced boundary layer flows with considerable skill, and we are developing a simple, one-dimensional, explanation of the key physical processes based on what we have learned from the complex 3D models.

APPROACH

The work involves theoretical development, numerical computations, and comparison with laboratory and field measurements. Our first two-phase flow model utilizes a mixture approach, where the properties of the mixture are functions of the sediment concentration. In the solid bed, in the regime of enduring contact between sediment particles, the bed is semi-rigid and resists a normal stress. In the interface region, between the sediment and water, where the concentration decreases, the mixture density and viscosity are dependent on the local concentration of sediment. The second model simulates the hydrodynamics directly, and uses standard relationships (Meyer-Peter, 1948; Bailard, 1981; Bagnold, 1966; etc.) for bed-load and suspended load transport based on the wall shear stress above the sand ripple. Then, by calculating the divergence of the local sediment transport, the bed height is integrated forward in time.

WORK COMPLETED

The model equations were described in detail in our last annual report. In the first model, we assume that a system containing sediment particles can be approximated as a mixture having variable density and viscosity that depend on the local sediment concentration and fluid-particle and particle-particle interactions are expressed through the mixture viscosity and a stress-induced diffusion term. In this approach, there are five governing equations that describe the flow field – the mixture continuity and three momentum equations and a species continuity equation for the sediment. The control volume

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approach on a three-dimensional staggered grid is used to solve the equations numerically. The turbulent dynamics of an initially stationary densely packed sand layer (60% by volume sand) in the approximate shape of a wave-orbital sand ripple, is coupled to a sinusoidally oscillating flow.

We have also developed a new one-dimensional model, based on conservation of volume and simple force balances, that shows that sand ripples of all types can develop because of the loss of kinetic energy to potential energy as the bed-load transport moves up a gentle slope. Consider, for example, a sand grain in the bed-load flow, moving at 10 cm/s, with mass, M, that has kinetic energy of: KE = ½ M v2 = 0.005 M (kg m2/s2). This KE will be lost to PE = M g h, when g h = 9.81 * h = 0.005, or h = 0.00051 m. That is, when the grain has risen only 0.5 mm, or approximately 2 grain diameters! This says that a very small perturbation in the height of the bed, will work, very effectively to trap other moving grains on the upslope side of the infinitesimal perturbation. In the linear regime, the bed stress is approximately constant along the bed, since the bedform is of sufficiently small amplitude that it does not cause flow separation or a sheltering effect on the lee side of the bedform. Here, a perturbation to the bed will grow steadily on the upslope side of the ripple, under oscillatory flow, in a weak flow regime, by accumulating, on alternating sides of the perturbation, more sand than is released on the downslope side. This occurs because the coefficient of static friction always exceeds the coefficient of dynamic friction, that is, it takes more force to initiate motion than it does to maintain motion, and the sand is trapped on the upslope side of the ripple because it loses it's kinetic energy, not just to friction with the bed, but primarily to potential energy. It is not necessary, in this model to completely arrest the motion of the bed-load layer, but merely to slow it down, causing a convergence of the mass flux on the upslope flank of the ripple, before the flow reverses direction under the oscillatory wave. In the non-linear ripple growth regime, the process is accelerated, because the stress on the lee-side of the ripple is weaker than the bed stress from the fluid flow on the upslope side of the ripple and in the trough. This produces a situation where there is progressively less initiation of motion, and a decreased loss of the mass from the down-slope flank of the crest of the ripple, where the boundary layer is fully attached to the ripple. In this case, the trapping dynamics (loss of kinetic to potential energy), that captures sand on the upslope side of the ripple is much more efficient than the release of the potential to kinetic energy on the down slope side. Hence, as the blocking effect increases with increasing ripple amplitude, the net accumulation of sand on the ripple increases as the ripple grows, and the process of ripple growth is naturally exponential in time, until other dynamics become of comparable magnitude. For a period of time, each side of the ripple takes turns, each wave period, being on the upslope side, as the flow oscillates from side to side, the ripple builds rapidly into a steep crested bed-form. These forces dominate until the third and final stage is reached, at the equilibrium amplitude, where the avalanche angle is approached, and just a little nudge on the down-slope side of the ripple is sufficient to release the potential energy of the uphill sand. When the balance is achieved between constructive forces, and destructive forces, then the ripple amplitude is stabilized. We are investigating the rate of growth of different wave lengths of sand ripples, for different specific wave orbital excursion lengths in an attempt to show why ripples of approximately 1.3 times the wave orbital excursion length are the most natural response from initially random bed perturbations.

RESULTS

The model does a good job of predicting concentration profiles and sea bed evolution over a few periods of wave oscillations. Our model is able to predict:

1). The growth of ripples, of the appropriate wave length, from a flat bed under oscillatory flow.
2). The growth of waves to the equilibrium height for different wave conditions.

3). The merging of sand ripples towards equilibrium conditions.
4). The contributions of bed load and suspended load to the growth or decay of ripples.
5). The shearing off of sand ripples to a flat bed when the flow becomes too energetic.
6). The splitting of a long ripple into short wavelength ripples for conditions where this should occur.

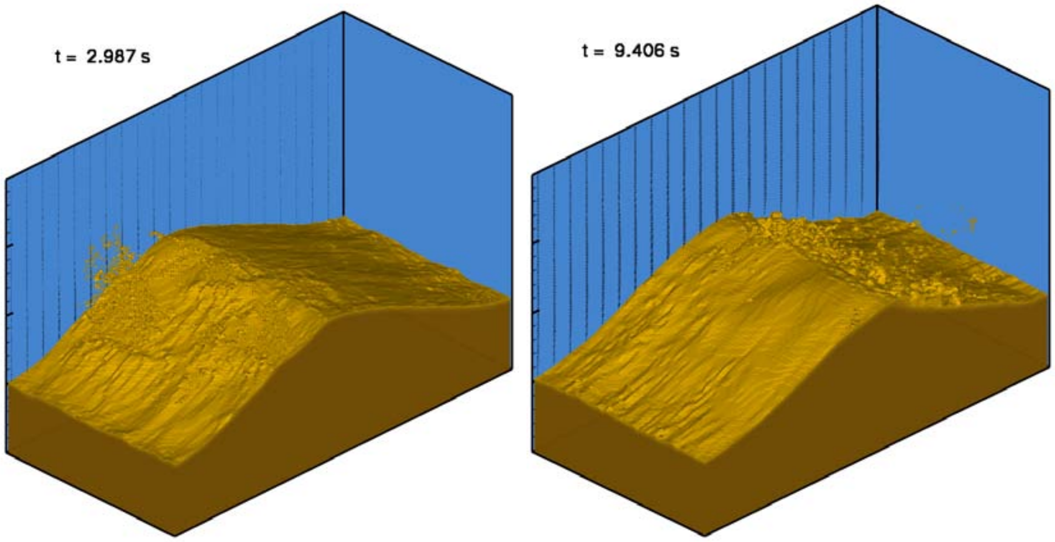

Figure 1. Concentration field of sand (brown contours) and velocity vectors of the sand ripple after 2.99 seconds (left panel) and after 9.4 seconds (right panel) showing sediment suspension and changes in the bedform after 3 wave periods. For this case the ripple length is 12 cm and the maximum wave orbital velocity is 40 cm/s.

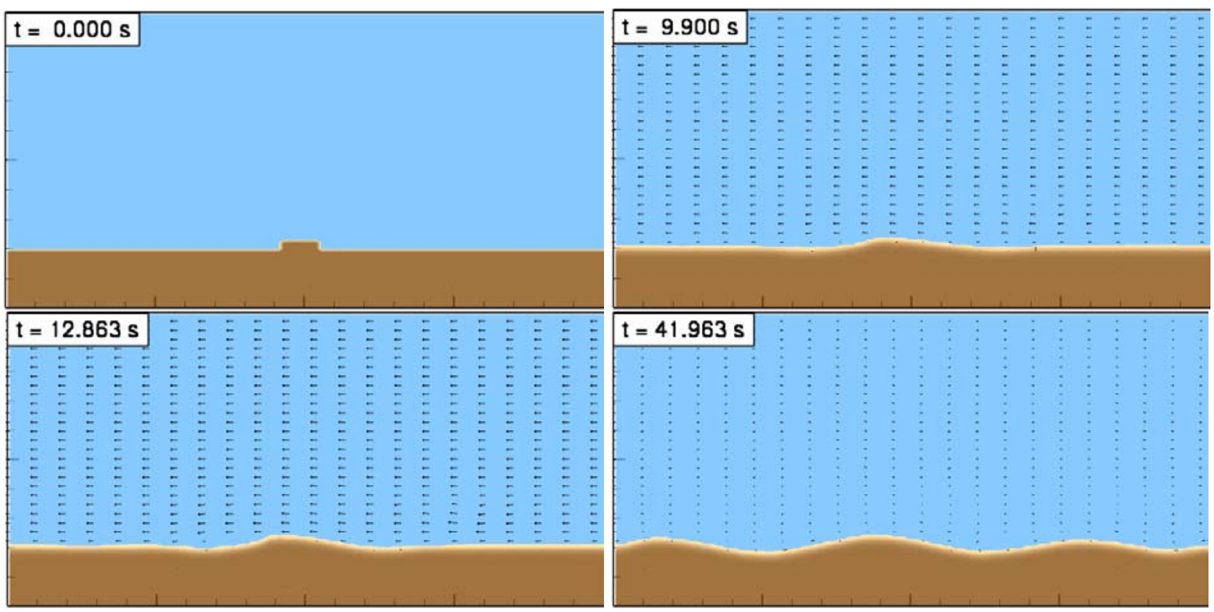

Figure 2. Concentration field of sand (color contours) and velocity vectors of the evolving sand ripple at t = 0.0, 9.9,12.8, and42.0 seconds. The simulation starts from a flat bed and develops ripples of wavelength similar to those found in laboratory studies. In this case, no suspended sediment is produced, and the entire evolution occurs through bed-load transport.

We have succeeded in dividing the sediment transport into bed load and suspended load contributions by considering the concentration and proximity to the immobile bed material. By integrating over time, from the beginning to the end of different simulations, we can show that bed load is the dominant mechanism for building sand ripples. Indeed, we can show that while bed load is busy building ripples, usually suspended load is busy leveling off the ripples. In cases of out-of-equilibrium ripples, where the ripples decay, our results show that bedload is the dominant mechanism for decreasing the amplitude of the ripple height, and interestingly, in this case, the suspended load actually contributes to building a taller ripple, because more of the suspended sediment lands on the crest of the ripple, that is sitting proud in the water column.

In our second modeling effort, using a traditional Bagnold-Bailord, parameterized bedload transport model, we have integrated the conservation equations to show the change of the bed topography with time. We have also implemented a suspended sediment sub-model, based on a pick-up function at the wall, related to the Shields stress.

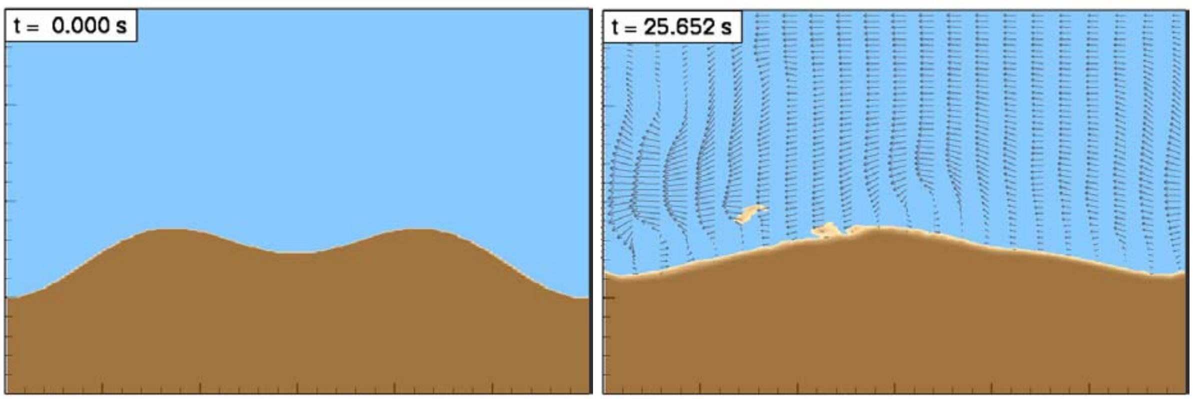

Figure 3. Simulation of a merging sand ripple. Starting conditions are of a double crested ripple, that evolves into a single crested ripple in approximately 25 seconds.

Simulations of coupled sand ripple and hydrodynamic response to wave driven currents have shown that stable sand ripples can develop after a few wave periods. The two-phase mixture approach, modified to include a rigid particle pressure force in the regime of enduring grain-to-grain contact has been successful at producing results qualitatively and quantitatively similar to those observed in laboratory experiments. A set of experiments has been conducted to determine the best formulation for the particle-pressure force as a function of concentration across the sediment – water interface. High resolution three-dimensional simulations take approximately 1 month to complete approximately 15 wave periods of simulation time. The mixture approach appears to have great promise. It has limitations, however, for example, it is presently only capable of simulating domains on the order of 20 cm x 10 cm x 10 cm on a side, given our computing environment. We have developed a second model for simulating larger domains, potentially capable of simulating domains on the order of 1 meter cubed (500 times larger domain than the mixture approach).

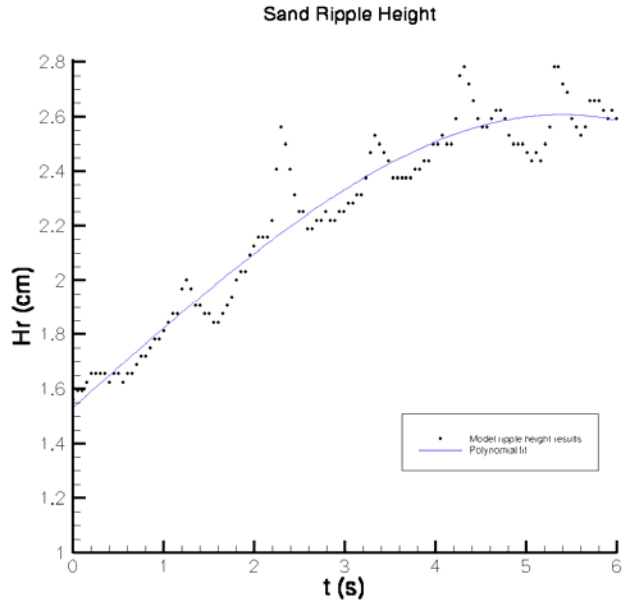

Figure 4. Time evolution of sand ripple height, defined as the difference in the vertical location of the packed bed at it's minimum in the trough and at it's maximum at the crest, calculated from where the sand concentration exceeds 95% of it's fully packed value.

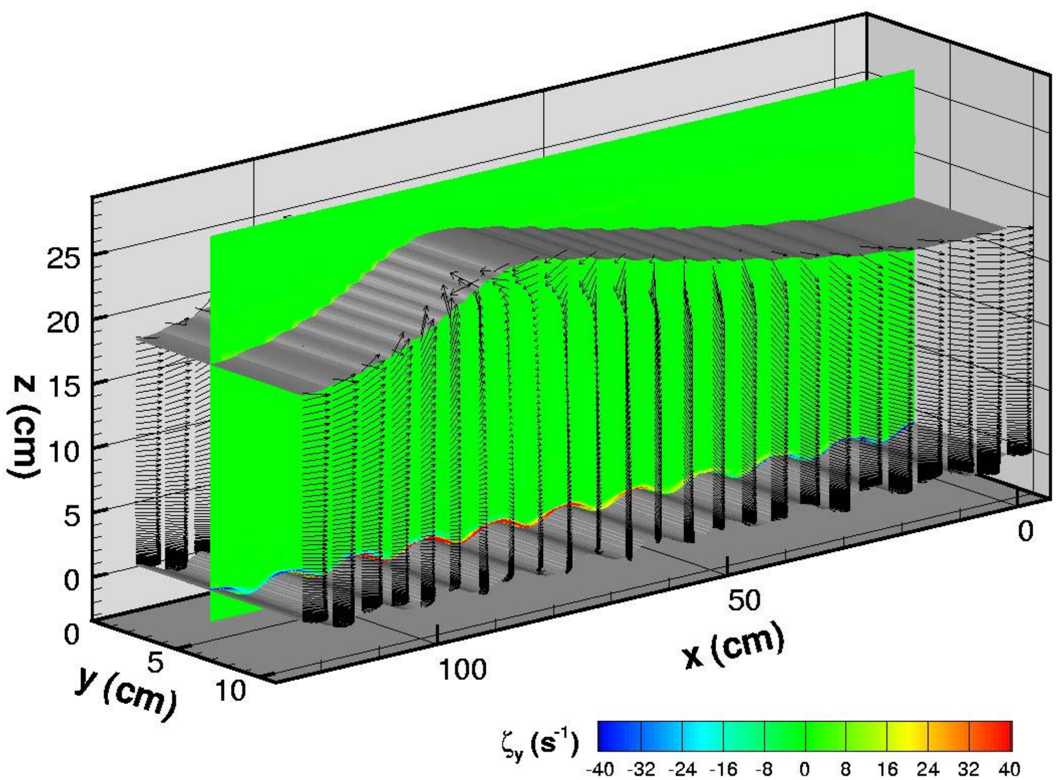

Figure 5. Flow field calculated using the second modeling approach, where the bed is updated based on standard bed-load and suspended load formulations for combined wave and current flow. Here the mean flow is perpendicular to the orientation of the sand ripples.

Our second modeling approach, implements the Meyer-Peter power law formulation and the Bagnold-Bailard-Inman (1981) bed-load and suspended load formulas and updates the bed position by integrating the divergence of the sediment flux through a sediment continuity equation:

$$\frac{\partial h}{\partial t}+\frac{\partial Q_x}{\partial x}+\frac{\partial Q_y}{\partial y}=0$$

. This model has also been coded and is in the testing phase. Present results suggest that the bulk formulas for Q are not readily adaptable for localized scour rates in the sand ripple regime. Figure 5 shows the flow field developing over an initialized sand ripple bed.

IMPACT/APPLICATIONS

Our models represent very new approaches. If they can be shown to predict sediment transport and ripple formation accurately significant new tools for understanding the dynamics of small scale sediment transort will be available.

RELATED PROJECTS

The ONR Sand Ripple DRI project has several related ongoing projects.

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